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PROGRESS REPORT & STATEMENT OF WORK FOR NAG5-5123

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Progress Report

1. Introduction

Our program is to perform a series of laboratory investigations designed to resolved significant atomic physics uncertainties that limit the interpretation of cosmic X-ray spectra. Specific goals include a quantitative characterization of Fe *L*-shell spectra; the development of new techniques to simulate Maxwellian plasmas using an electron beam ion trap (EBIT); and the measurement of dielectronic recombination rates for photoionized gas. New atomic calculations have also been carried out in parallel with the laboratory investigations.

2. Accomplishments during the Grant Period.

The period of performance under this grant cycle officially began 24 February 1997 and continues until 31 January 1998. Our initial proposal involved a multi-faceted program of research including measurements of collisional processes in highly charged ions using the Lawrence Livermore National Laboratory EBIT, atomic calculations using the Hebrew University-Lawrence Livermore Atomic Code (HULLAC), and the analysis and interpretation of existing data obtained from the Princeton Large Torus tokamak. During the period covered by the grant we also continued our collaboration with scientists at the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg, Germany, and have carried out several experiments using the heavy-ion storage test storage ring located at MPIK.

A number of publications and conference proceedings have resulted from our program. Short synopses of these results are given in the subsections below.

2.1 High Resolution Measurements of the Iron $K\alpha$ Spectra (Decaux *et al.* 1997, Jacobs *et al.* 1997).

Using EBIT, we have carried out laboratory measurements, using EBIT, of high resolution spectra of Fe XVIII to Fe XXV $K\alpha$ emission under transient conditions similar to those that are believed to exist in stellar flares and young supernova remnants. Taking advantage of our high spectral resolution ($\lambda/\Delta\lambda \geq 2000$), we identify a number of transitions that can serve as diagnostics of ionizing plasmas. By varying the excitation energy in the experiments, we constrain the effects of the electron distribution on these diagnostic lines. Using our measured line ratios, we deduce values for the ionization time, $\eta = N_e t$, in the plasma, which agree with the actual values to $\sim 20\%$ accuracy. This adds confidence to our ability to derive similar constraints on astrophysical plasmas from remote X-ray spectroscopic observations.

2.2 Measurements of *L*-shell Line Emission in Fe XVII to Fe XXIV (Beiersdorfer *et al.* 1997a, Beiersdorfer *et al.* 1997b, Brown *et al.* 1997, Gu *et al.* 1997).

The upcoming *AXAF* and *XMM* satellite missions will provide an unprecedented wealth of high-resolution X-ray data that will make it possible to use line diagnostics to determine the physical properties of a large number of cosmic sources. The interpretation of these data will require accurate and complete spectral models. Fe *L*-shell emission is of special interest because it provides intense spectral features stretching from

6 to 18 Å. It is, however, among the least well understood set of emission features in the X-ray band. In order to address questions that arise in constructing accurate and complete spectral models, we are undertaking an intense laboratory effort to study L -shell spectra from Fe XVII through Fe XXIV. First we are building a list of all relevant L -shell lines from these charge states. This includes identifying forbidden transitions, such as the $3p \rightarrow 2p$ electric quadrupole transitions in Fe XVII at 16.350 and 13.153 Å, and all the transitions from high- n levels to $n = 2$ that contribute to the X-ray flux at the higher X-ray energies but are typically missing from the spectral codes. Second, we are determining the importance of various line formation processes in the excitation of a given line in order to ensure that all significant processes will be included in the emission models. We show, for example, that resonance processes (*e. g.*, dielectronic recombination and resonant excitation) are significant contributors to the strong Fe XXIV $3 \rightarrow 2$ transitions. Third, we are accurately measuring line intensities to test atomic theory. This includes tests of the predicted ratios of the $3 \rightarrow 2$ and $4 \rightarrow 2$ emission ratio in Fe XXIV as well as the $3d \rightarrow 2p$ $^1P_1, ^3D_1$ ratio in Fe XVII, where there is wide scatter among theoretical predictions.

2.5 Dielectronic Recombination in Photoionized Gas (Savin *et al.* 1997a, Savin *et al.* 1997b).

At the low electron temperatures existing in photoionized gases with cosmic abundances, dielectronic recombination (DR) proceeds primarily via $nl_j \rightarrow nl'_j$, excitations of core electrons ($\Delta n = 0$ DR). At these temperatures, the dominant DR channel often involves $2p_{1/2} \rightarrow 2p_{3/2}$ fine-structure core excitations, which are not included in LS -coupling calculations or the Burgess formula. Using the heavy-ion storage ring at the Max-Planck-Institute for Nuclear in Heidelberg, Germany, we have verified experimentally for Fe XVIII that DR proceeding via this channel can be significant in relation to other recombination rates, especially at the low temperatures characteristic of photoionized gases. At temperatures in photoionized gases near where Fe XVIII peaks in fractional abundance, our measured Fe XVIII to Fe XVII $\Delta n = 0$ DR rate coefficient is a factor of ~ 2 larger than predicted by existing theoretical calculations. We have provided a fit to our measured rate coefficient for ionization equilibrium models. We have carried out new fully-relativistic calculations using intermediate-coupling which include the $2p_{1/2} \rightarrow 2p_{3/2}$ channel and agree to within $\sim 30\%$ with our measurements. DR via the $2p_{1/2} \rightarrow 2p_{3/2}$ channel may also have spectroscopic implications, providing unique spectral signatures at soft X-ray wavelengths which could provide good electron temperature diagnostics.

2.6 Observation and Modeling of High- n Iron L -Shell Lines (Wargelin *et al.* 1997).

The spectra of highly ionized iron species between 7 and 9 Å have been studied using data obtained at the Princeton Large Torus tokamak under plasma conditions similar to those present in stellar flares. The wavelengths of many iron lines are measured with very high accuracy ($\lambda/\Delta\lambda$ up to 40,000). Theoretical spectra that predict both the wavelength and intensity of Fe emission lines are compared with the observed spectra and used to make accurate line identifications. Virtually all the observed iron lines are found to arise from $n = 4, 5$, and $6 \rightarrow 2$ transitions in Fe XXI to Fe XXIV, and many lines are identified for the first time. Several transitions have been shown to have diagnostic applications, and a detailed analysis of the density sensitivity of Fe XXII lines has been carried out. In addition, a number of emission lines from heliumlike Mg XI and Al XII, which may be useful as plasma diagnostics, have been observed in the 7 – 9 Å wavelength range. We have found that some of the more important Mg XI and Al XII lines are, in fact, blended with lines from Fe XXII, XXIII, and XXIV. These previously unknown blends will need to be taken into account when attempting to use these Mg and Al lines as plasma diagnostics.

2.7 Simulating a Maxwellian Plasma using an Electron Beam Ion Trap (Savin *et al.* 1997c).

In a collisionally dominated plasma, the ionization structure and line emission of a plasma is determined by electron collisions. These electrons are typically expected to have a Maxwell-Boltzmann energy distribution. We are attempting to use the Lawrence-Livermore EBIT to simulate a single electron density plasma with a Maxwell-Boltzmann electron energy distribution. Our aim is to produce the ionization balance appropriate for a Maxwellian plasma and to observe the resulting line emission. Achieving the ionization balance appropriate for a Maxwellian plasma is important because line emission from a given charge state is coupled to the one lower charge state by inner shell ionization and to the one higher charge state by dielectronic and radiative recombination.

We have recently demonstrated that the concept of producing quasi-Maxwellian plasmas can be implemented in EBIT by sweeping in time both the electron beam energy and electron gun anode voltage.

Because the electron beam current varies as $n_e E^{1/2}$, we must also sweep the anode (extraction) voltage of the electron gun in EBIT synchronously with the beam energy, so as to vary the current in such a way as to keep the electron density nearly constant. Initial results have demonstrated that the concept of producing quasi-Maxwellian plasmas can be implemented in EBIT by sweeping in time both the electron beam energy and the electron gun anode voltage.

3. Statement Work for Year 2

In the second year of the grant we will carry out the following work:

- Continue our EBIT measurements of the effects of resonant processes on Fe L -shell line emission.
- Study Fe L -shell line emission under quasi-Maxwellian conditions.
- Complete the analysis of heliumlike Ne line emission measurements.
- Continue the storage ring measurements of L -shell iron dielectronic recombination measurements.

4. Conclusions

During the period of this grant cycle we have carried out a number of measurements and calculations of iron L - and K -shell line emission. Our new calculations have demonstrated some of the short-comings in the atomic data used in the current generation of emission line codes. Measurements of iron L -shell line emission have benchmarked some of the newly calculated atomic data. Iron L -shell spectral measurements have also resulted in the observation and identification of many previously unknown iron lines, some of which blend with important heliumlike Mg and Al line diagnostics. Measurements of iron K -shell spectra have demonstrated the potential utility of $K\alpha$ line emission for studying ionizing plasmas. Measurements of DR have discovered the previously unrecognized importance of DR via forbidden core excitations of the recombining ion. Significant progress has also been made in the development of new techniques to simulate a Maxwellian plasma using EBIT. In the upcoming year we will continue and extend our results

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